Putrescine production via the agmatine deiminase pathway increases the growth of *Lactococcus lactis* and causes the alkalinization of the culture medium

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Abstract

Lactococcus lactis is the most important starter culture organism used in the dairy industry. Although *L. lactis* species have been awarded Qualified Presumption of Safety status by the European Food Safety Authority, and Generally Regarded as Safe status by the US Food and Drug Administration, some strains can produce the biogenic amine putrescine. One such strain is *L. lactis subsp. cremoris* CECT 8666 (formerly *L. lactis* subsp*. cremoris* GE2-14), which was isolated from Genestoso cheese. This strain catabolizes agmatine to putrescine via the agmatine deiminase (AGDI) pathway, which involves the production of ATP and two ammonium ions. The present work shows that the availability of agmatine and its metabolization to putrescine allows for greater bacterial growth (in a biphasic pattern) and causes the alkalinization of the culture medium in a dose-dependent manner. The construction of a mutant lacking the AGDI cluster (*L. lactis* CECT 8666 Δ*agdi*) confirmed the latter's direct role in putrescine production, growth and medium alkalinization. Alkalinization did not affect the putrescine production pattern and was not essential for increased bacterial growth.

Keywords: *Lactococcus lactis;* biogenic amines; putrescine; agmatine deiminase; AGDI cluster; bacterial growth

Introduction

The ability of *Lactococcus lactis* - a lactic acid bacterium (LAB) - to rapidly ferment lactose, its notable proteolytic activity and its production of flavor molecules (Beresford et al. 2001; Kelly et al. 2010; Kuipers, 2001), have made it one of the most commonly used primary starters in the manufacture of cheese, fermented milk, sour cream and buttermilk. *L. lactis* has been granted Qualified Presumption of Safety status by the European Food Safety Authority, and Generally Regarded as Safe status by the US Food and Drug Administration.

However, our group has characterized several *L. lactis* subsp*. lactis* and *L. lactis* subsp*. cremoris* strains from dairy products that produce the biogenic amine (BA) putrescine (Ladero et al. 2011b). Indeed, putrescine-producing *L. lactis* has been detected in high concentrations in a number of cheeses (Ladero et al. 2012a). Along with tyramine and histamine, putrescine is one of the most common BAs in dairy products (Fernandez et al. 2007). Its presence in fermented foods confers undesirable flavors (Ladero et al. 2012c) and it can have toxic effects when ingested, such as increased cardiac output, tachycardia and hypotension. It can also potentiate the effects of other BAs (Ladero et al. 2010; Romano et al. 2012). It may even have a role in promoting malignancy: it is known to be involved in growth-related processes and has been suggested to increase intestinal and colonic tumorigenesis and neoplasm proliferation (Gerner and Meyskens, 2004; Ignatenko et al. 2006; Ladero et al. 2010; Seiler et al. 1998).

In *L. lactis*, putrescine is produced through the catabolism of agmatine, a decarboxylated derivative of arginine (Simon and Stalon, 1982), via the agmatine deiminase (AGDI) pathway (Ladero et al. 2011b) (Fig. 1a). This metabolic pathway involves the sequential action of three enzymes: agmatine deiminase (AguA), putrescine carbamoyltransferase (AguB) and carbamate kinase (AguC). Agmatine is deiminated by AguA, rendering one ammonium ion and N-carbamoyl putrescine, which is phosphorylated by AguB to produce putrescine and carbamoyl phosphate. This last product is used as a substrate for ADP phosphorylation by AguC, a reaction that renders one molecule of ATP and another ammonium ion. Putrescine is then exchanged with external agmatine by the agmatine/putrescine antiporter (AguD). The gene cluster organization for agmatine catabolism in *L. lactis* (Fig. 1b) seems to be unique among LAB, the potential regulatory gene *aguR* being located upstream of the catabolic genes and orientated in the same direction (Ladero et al. 2011b). The catabolic genes are organized as follows: *aguB* (encoding AguB), *aguD* (encoding AguD), *aguA* (encoding AguA) and *aguC* (encoding AguC). Transcriptional analysis of the AGDI cluster of *L. lactis* subsp. *lactis* (Ladero et al. 2011b) and *L. lactis subsp. cremoris* CECT 8666 (formerly *L. lactis* subsp. *cremoris* GE2-14) (Linares et al. 2013) has shown that the catabolic genes together form the *aguBDAC* operon, and that they are transcribed as a single polycistronic mRNA.

Although the genetics and transcriptional regulation of putrescine production have been characterized in *L. lactis* (Ladero et al. 2011b; Linares et al. 2013) the

physiological role of putrescine production in this organism has not been studied. In the present work, *L. lactis* subsp. *cremoris* CECT 8666, isolated from an artisanal cheese and previously selected as a model putrescine-producing strain (Linares et al. 2013), was used to assess the effect of putrescine production on bacterial growth and on the alkalinization of the culture medium.

Material and Methods

Bacterial strains and culture conditions

Table1 shows the bacterial strains used. *L. lactis* subsp. *cremoris* GE2-14, the putrescine-producing strain used in this study, was previously isolated from Genestoso cheese, a Spanish artisanal cheese made from raw milk without the addition of commercial starter cultures (Fernandez et al. 2011; Ladero et al. 2011b). *L. lactis* subsp. *cremoris* GE2-14 was deposited in the Colección Española de Cultivos Tipo (CECT) with the accession No CECT 8666. *L. lactis* CECT 8666 and the derivative agmatine deiminase mutant (*L. lactis* CECT 8666 Δ*agdi*), were grown in M17 (Oxoid, UK) supplemented with 0.5% (w/v) glucose (GM17) (unless otherwise indicated) at 32ºC without aeration. Where indicated, the medium was supplemented with 20 mM of agmatine (GM17+A) (Sigma-Aldrich, St. Louis, MO). For all fermentation assays, overnight cultures of *L. lactis* strains were used (1% v/v inoculum).

pH-uncontrolled fermentations were performed in 30 ml of GM17 or GM17+A. Sampling (2 ml) was performed every hour for 12 h. The pH of the samples was measured using a CRISON miCropH 2001 pH-meter (Crison Instruments S.A., Barcelona, Spain). For pH-controlled fermentations, cells were grown in a Six-Fors® bioreactor (Infors AG, Bottmingen, Switzerland) containing 300 ml of GM17+A. The reactor was maintained at 32°C, stirring at 50 rpm, and with zero air input. The fixed pH of 5.5 was maintained by the automatic addition of 1 N NaOH or 1 N HCl, as needed. 2 ml samples were collected each hour. Microbial growth was examined in all cultures by measuring absorbance at 600 nm (OD_{600}) using a spectrophotometer (Eppendorf, NY, USA). Putrescine, agmatine and ammonium ion concentrations were analyzed as explained below.

Putrescine, agmatine and ammonium ions: analysis by ultra-high performance liquid chromatography

Sample supernatants were obtained by centrifugation (2000 x *g* for 15 min). Putrescine, agmatine and ammonium ions were analyzed by ultra-high performance liquid chromatography (UHPLC) using a Waters H-Class ACQUITY UPLC® apparatus controlled by Empower 2.0 software and employing a UV-detection method based on derivatization with diethyl ethoxymethylene malonate (Sigma-Aldrich), following the protocol of (Redruello et al. 2013).

DNA manipulation procedures

L. lactis total DNA was extracted using Kirby lytic mix according to Hopwood et al. (1985). Plasmid DNA was prepared from *Escherichia coli* by the alkaline lysis method (Green et al. 2012). Restriction endonuclease digestions, alkaline phosphatase treatments, ligations and other DNA manipulations were performed according to standard procedures (Green et al. 2012). The DNA modification enzymes were from commercial sources and used following the supplier's recommendations. Electrotransformation of *E. coli* was achieved in a Bio-Rad pulser using protocols provided by the supplier; *L. lactis* was electrotransformed as described by de Vos et al. (1989). PCR amplifications were performed in a MyCycler™ thermal cycler (Bio-Rad, Spain) using Phusion High-Fidelity DNA polymerase (Thermo Scientific, Spain) according to the manufacturer's protocol. All DNA fragments amplified were checked by nucleotide sequencing at Macrogen Inc. (Seoul, Republic of Korea).

Construction of the L. lactis CECT 8666 Δ*agdi mutant*

The *L. lactis* CECT 8666 Δ*agdi* mutant lacking the AGDI cluster (GenBank Accession No HG317493.1) was constructed by homologous recombination, using the selection/counter-selection vector pCS1966 (Solem et al. 2008). Table 1 shows the primers and plasmids used to generate the AGDI knock-out. The primers were designed to include the following restriction recognition sites: SpeI in primer KO-214AguR-AF2, PstI in KO-214AguR-AR, PstI in CKPstF, and XhoI in NoxXho. A

826 bp PCR fragment containing a 610 bp fragment of the *ycaC* gene (the gene upstream from *aguR*, GenBank Accession No HG317493.1), the intergenic region between *ycaC* and *aguR*, and the encoding sequence of the five first amino acids of the *aguR* gene of *L. lactis* CECT 8666, was amplified using primers KO-214AguR-AF2 and KO-214AguR-AR. The amplification conditions were: 1 min of initial denaturation at 98°C, followed by 35 amplification cycles (denaturation for 30 s at 98°C, annealing for 30 s at 55°C, and extension for 1 min at 72°C), and a final extension step of 10 min at 72°C. The resulting fragment was digested with the restriction enzymes SpeI and PstI and cloned into the pCS1966 vector, rendering the plasmid pIPLA1269. A second 889 bp PCR fragment containing the last 260 bp of the *aguC* gene plus the last 427 bp of the *yrfB* gene (the gene downstream of *aguC*, GenBank Accession No HG317493.1) and the intergenic region of *aguC* and *yrfB*, were PCR amplified using primers CKPstF and NoxXho. The amplification conditions were: 1 min of initial denaturation at 98°C, followed by 35 amplification cycles (denaturation for 30 s at 98°C, annealing for 30 s at 55°C, and extension for 1 min at 72°C), and a final extension step for 10 min at 72°C. The resulting fragment was digested with PstI and XhoI and cloned into the plasmid pIPLA1269, rendering the plasmid pIPLA1292. Plasmid pIPLA1292 was then transformed into *L. lactis* CECT 8666 electrocompetent cells and mutant bacteria lacking the AGDI cluster were selected following the method of Solem et al. (2008). *L. lactis* CECT 8666 Δ*agdi* mutants were confirmed by nucleotide sequence analysis of the amplicon obtained using the primers KO-214AguR-AF2 and NoxXho, which

rendered the expected 1715 bp fragment instead of the 7112 bp fragment corresponding to the wild type strain (data not shown).

Results

Putrescine production, bacterial growth and pH

The production of putrescine was monitored over the growth curve. Figure 2A shows that the *L. lactis* CECT 8666 grown in GM17+A accumulated 20 mM of putrescine 10 h after inoculation (during the stationary phase) (Fig. 2b). Putrescine production was first detected after 6 h of fermentation and it was continuously produced over the next 4 h until the agmatine was used up. Figure 2A shows that putrescine production strictly followed agmatine consumption. Concomitant production of ammonium ions was also observed (Fig. 2a).

A typical growth curve was recorded over 10 h for the culture grown in GM17, with an exponential growth phase starting after 2 h of inoculation and lasting until 5 h of fermentation (OD_{600} 3.6). At this point the culture entered the stationary phase, in which it remained until the end of fermentation (Fig. 2b). However, the culture grown in GM17+A shown a biphasic growth curve typical of diauxic growth. The first exponential growth phase lasted until 5 h of fermentation, as described above for the GM17-grown cultures, but the stationary growth phase lasted only 1 h before a second growth phase set in. This lasted until 10 h of fermentation. At the

end of this second growth phase in the GM17+A-grown cultures, the OD_{600} was much higher (4.2) than that recorded for the GM17 cultures (3.2) (Fig. 2b).

The change in the pH of the culture media was also monitored (Fig. 2b). The growth of *L. lactis* CECT 8666 in both GM17 and GM17+A induced an acidification of the medium from pH 6.9 to pH 5.8 by 5 h post-inoculation. However, the pH of the culture grown in GM17 remained at pH 5.8 until the end of fermentation, while the pH of the GM17+A medium alkalinized, reaching a final pH of 6.5. The alkalinization of the medium in the culture supplemented with agmatine paralleled the production of ammonium ions, a result of the catabolism of agmatine to putrescine (Fig. 2a).

Effect of agmatine concentration on bacterial growth and pH

To confirm the correlation between putrescine production and both the enhancement of growth and the alkalinization of the culture medium, *L. lactis* CECT 8666 was grown in GM17 supplemented with increasing amounts of agmatine (0, 1, 5, 10 and 20 mM). Figure 3 shows the accumulation of putrescine, the production of ammonium ions, agmatine consumption, microbial growth (OD_{600}) and the pH of the culture medium over time. Putrescine accumulation (Fig. 3a) and ammonium ion production (Fig. 3b) depended on the starting concentration of the agmatine in the medium (Fig. 3c). As expected from the stoichiometry of the reaction (Fig. 1a), the ammonium ion concentration was twice that of the

putrescine. Interestingly, putrescine was first detected after 6 h of incubation, independent of the agmatine concentration. Agmatine was consumed as putrescine was produced (Fig. 3c). Agmatine concentrations of 1 and 5 mM were used up by 8 h; concentrations of 10 and 20 mM lasted 2 h more. After 10 h of culture almost all the agmatine had been catabolized to putrescine, independent of the initial agmatine concentration.

Differences in bacterial growth were observed depending on the agmatine concentration (Fig. 3d). Cultures supplemented with 20 mM agmatine showed the second growth phase described above and an increase in the final OD_{600} compared to cultures without agmatine (OD_{600}=4.48 and OD_{600}=3.48 respectively). Cultures supplemented with 10 mM agmatine showed a slight increase in the second stationary phase OD_{600} compared to those with no added agmatine (OD_{600}=4.09 and OD_{600}=3.48 respectively), although in cultures supplemented with 20 mM agmatine, the second growth phase was not as clear. In contrast, cultures supplemented with 1 and 5 mM agmatine showed bacterial growth similar to that seen for those with no added agmatine. Alkalinization of the medium was also clear in the cultures supplemented with agmatine above 5 mM (Fig. 3e). The initial pH of the culture medium (pH 6.9) acidified to pH 5.4 by 6 h of fermentation. After this time, the pH of the cultures supplemented with agmatine (5 mM and above) became alkalinized at higher agmatine concentration and in a manner proportional to the ammonium ion production (Fig. 3e). Agmatine concentrations below 5 mM

had no significant effect on the pH, which remained at pH 5.4, as for cultures grown without agmatine.

Role of the AGDI cluster in putrescine production, bacterial growth and pH

To confirm the involvement of the AGDI cluster in the catabolism of agmatine to putrescine, and its effect on bacterial growth and changes in pH, an *L. lactis* CECT 8666 Δ*agdi* mutant lacking the AGDI cluster was constructed (see Material and Methods section 2.4). Both, wild type (wt) and Δ*agdi* mutant strains were grown in GM17 and GM17+A for 10 h and samples collected every hour to determine putrescine production, microbial growth and the pH of the culture medium (Fig. 4). As expected, the deletion of the AGDI cluster completely abolished the catabolism of agmatine to putrescine, whereas 10 mM putrescine was accumulated in the wt culture (Fig. 4a). In addition, the deletion of the AGDI cluster resulted in the absence of the second growth phase when cells were grown in GM17+A (OD_{600}=3.59 compared to OD_{600}=4.41 for wt cultures) (Fig. 4b). Moreover, medium alkalinization was only detectable in wt cultures grown in GM17+A (Fig. 4c). The Δ*agdi* mutant culture did not alkalinize the culture medium, and the pH (5.52) reached after 7 h was maintained over the rest of the fermentation (Fig. 4c), as seen for the wt and Δ*agdi* cultures grown in GM17.

The alkalinization caused by the AGDI pathway has no effect on bacterial growth

The effect of culture medium alkalinization due to putrescine production in GM17+A, and its involvement in the regulation of putrescine production, was also examined. For this, wt and Δ*agdi* mutant cultures were grown independently in a Six-Fors® bioreactor containing 300 ml of GM17+A. No control of pH was imposed until it reached 5.6 (after 5 and 6 h of fermentation, for the wt and Δ*agdi* cultures respectively); it was then fixed by the bioreactor at 5.6. Putrescine production, bacterial growth and pH were monitored for 12 h (Fig. 5). The putrescine production pattern for the wt (Fig. 5b) was similar to that of cultures grown with no pH control (Fig. 2a, 3a and 4a), in which putrescine production started after 6 h of fermentation and an accumulation of 12 mM putrescine was recovered by 12 h. As expected, no putrescine production was detected in the Δ*agdi* mutant cultures. Further, the absence of alkalinization did not prevent the appearance of a second growth phase in the wt culture after 12 h of fermentation (Fig. 5c). These results suggest that culture medium alkalinization is not essential for the increase in growth observed in wt cultures grown in GM17 supplemented with 20 mM agmatine.

Discussion

Putrescine is a BA frequently found in fermented products (Garcia-Villar et al. 2009; Ladero et al. 2011a) and one of the most abundant in dairy products (Fernandez et al. 2007; Ladero et al. 2010), in which LAB species such as *Enterococcus faecalis*, *Enterococcus hirae*, *Lactobacillus brevis* and *Lactobacillus*

curvatus have all been identified as producers (Ladero et al. 2012b; Ladero et al. 2011b). Recently, our group reported that *L. lactis* subsp. *lactis* and *L. lactis* subsp. *cremoris* were also putrescine producers in dairy products, and that in some cases putrescine concentrations could reach high concentrations (Ladero et al. 2011b; Ladero et al. 2012b).

Until now, the physiological role of putrescine production in *L. lactis* had not been studied. The present work reports the direct involvement of the AGDI pathway in enhancing the growth of *L. lactis* CECT 8666 when grown in a medium supplemented with agmatine concentrations higher than the usually found in milk and dairy products (Galgano et al. 2012). In fact, cultures grown in medium supplemented with agmatine concentrations above 5 mM underwent a second growth phase, while cultures with no agmatine remained in the stationary phase (Fig. 2b and 3d). This effect was completely abolished in the Δ*agdi* mutant, which lacks the AGDI cluster (Fig. 4b), suggesting a direct role for the AGDI pathway in enhancing bacterial growth in the presence of agmatine. It would seem clear that the catabolism of agmatine via this pathway enables *L. lactis* to reach higher cell densities in fermentative media. This effect of agmatine catabolism on bacterial growth has also been observed in *E. faecalis*, the presence of 10 mM agmatine increasing growth by 60% (Suarez et al. 2013). However, this is not a general effect in all microorganisms that use the AGDI pathway. For example, in *Streptococcus mutants* putrescine production enhances acid tolerance and

contributes to the competitive fitness of the organism at low pH, but does not increase its growth (Griswold et al. 2006).

Unlike *Pseudomonas aeruginosa* (Chou et al. 2008), in which putrescine is catabolized as a source of energy, *L. lactis* CECT 8666 was unable to further metabolize putrescine and it was fully exported to the extracellular medium. This suggests that the effect of its presence on cell growth is not due to the putrescine alone, but a consequence of other products of agmatine catabolism, i.e., ATP and ammonium ions. According to the stoichiometry of the AGDI pathway in *L. lactis,* one mole of agmatine renders one mole of putrescine, 1 mole of ATP, and 2 moles of ammonium ions (Ladero et al. 2011b) (Fig. 1a), which causes the alkalinization of the medium. However, this increase in the pH of the culture medium does not seem to be responsible for the increase in growth in the presence of agmatine; growth was similar (biphasic) whether the pH was fixed at pH 5.6 (Fig. 5) or left uncontrolled (Figs. 2b, 3d, 4b), despite the putrescine production was faster and the final growth higher in cultures with no pH control. The ATP generated during the catabolism of agmatine results in additional energy that would help to improve the growth and competitiveness of the bacteria. This is reminiscent of the arginine deiminase pathway (ADI) in *L. lactis*, which catabolizes arginine into ornithine and improves the survival of the bacteria by supplying them with additional energy (Larsen et al. 2004).

Two interesting effects were observed when the cells were grown in the presence of agmatine. Independent of the initial amount of agmatine present in the culture, putrescine production was not observed until the beginning of the stationary phase. (Fig. 2a and Fig. 3a). Indeed, in those cultures with an agmatine concentration of over 5 mM, a second growth phase was observed (Fig. 2b and Fig. 3d). These effects were not observed with the mutant strain (Fig. 4b), indicating the involvement of the AGDI cluster. The biphasic growth curve observed in *L. lactis* CECT 8666 when grown in the presence of agmatine is typical of the diauxic growth that bacteria show when they grow in the presence of two alternative sugars (Cai et al. 2012; Okada et al. 1981; Solopova et al. 2014). The most-preferred sugar, generally glucose, is metabolized during a first growth cycle until it is exhausted. The cells then enter a stationary phase before starting to metabolize the less-preferred carbon source, whereupon they enter a second growth cycle. This would seem to be the pattern followed for agmatine utilization in *L. lactis* subsp. *cremoris* CECT 8666. In fact, recent studies have shown that agmatine utilization in this strain is subjected to catabolite repression (Linares et al. 2013). The regulatory mechanism seems to involve the negative regulation of the transcription of the *aguBDAC* operon via carbon catabolite protein A (CcpA), which exerts its effect by binding to a *cre* site downstream of the -10 region of the *aguBDCA* promoter (Linares et al. 2013). This would explain the delay seen in putrescine production, which would be impaired until the culture leaves the stationary phase and enters the second growth phase during which agmatine is used, and putrescine, ATP and ammonium ions are produced.

Traditionally, the production of BA was thought to be involved with acid stress resistance in prokaryotes (Linares et al. 2011; Spano et al. 2010); indeed, such a role for the AGDI pathway has been suggested in *S. mutants* (Griswold et al. 2006; Griswold et al. 2009), *L. brevis* (Lucas et al. 2007) and *E. faecalis* (Llacer et al. 2007). These microorganisms seem to use the ammonium ions generated by the ADGI pathway to neutralize any increase in acidity. In *L. lactis* subsp. *cremoris* CECT 8666, ammonium ions were produced and accumulated in the extracellular medium as result of agmatine deamination, and an agmatine dose-dependent alkalinization of the medium was recorded in those cultures supplemented with concentrations of over 5 mM (Fig. 3). At first sight, the alkalinization of the medium would seem to agree with the idea that BA biosynthesis in lactic acid bacteria represents a system for resisting acid stress in fermentative environments (Bearson et al. 1997; Wolken et al. 2006). However, putrescine production was not essential for the enhancement of growth observed following the first stationary phase; the artificial maintenance of the pH at pH 5.6, did not impair the growth promoted by agmatine (Fig. 5).

Together, the present results indicate that, in *L. lactis* subsp. *cremoris* CECT 8666, agmatine provides an alternative source of energy via the AGDI pathway, allowing for renewed growth after the culture enters the stationary phase following the depletion of more preferred carbon sources. This reiterates the need to select starter strains that do not produce BAs. Apart from the obvious food safety issue

surrounding the presence of putrescine in dairy products, and the fact that it can affect their organoleptic characteristics, the presence of putrescine-producing *L. lactis* strains could adversely affect the process of acidification during fermentation. Further, in the presence of agmatine, putrescine-producing *L. lactis* strains could have a selective advantage over the *L. lactis* strains with no AGDI pathway activity.

Acknowledgements

This work was performed with the financial support of the Spanish Ministry of Economy and Competitiveness (AGL2013-45431-R) and the CSIC (201270E144). B. del Rio and D. Linares were beneficiaries of a JAE DOC contract (CSIC). The authors thank Adrian Burton for linguistic assistance.

References

Bearson S, Bearson B, Foster JW (1997) Acid stress responses in enterobacteria. FEMS Microbiol Lett 147, 173-180

Beresford TP, Fitzsimons NA, Brennan NL, Cogan TM (2001) Recent advances in cheese microbiology. Int Dairy J 11, 259-274

Cai J, Tong HC, Qi FX, Dong XZ (2012) CcpA-Dependent Carbohydrate Catabolite Repression Regulates Galactose Metabolism in *Streptococcus oligofermentans*. J Bacteriol 194, 3824-3832

Chou HT, Kwon DH, Hegazy M, Lu CD (2008) Transcriptome analysis of agmatine and putrescine catabolism in *Pseudomonas aeruginosa* PAO1. J Bacteriol 190, 1966-1975

de Vos WM, Vos P, de Haard H, Boerrigter I (1989) Cloning and expression of the *Lactococcus lactis* subsp. *cremoris* SK11 gene encoding an extracellular serine proteinase. Gene 85, 169-176.

Fernandez E, Alegria A, Delgado S, Martin MC, Mayo B (2011) Comparative phenotypic and molecular genetic profiling of wild *Lactococcus lactis* subsp. *lactis* strains of the *L. lactis* subsp. *lactis* and *L. lactis* subsp. *cremoris* genotypes, isolated from starter-free cheeses made of raw milk. Appl Environ Microbiol 77, 5324-5335

Fernandez M, Linares DM, del Rio B, Ladero V, Alvarez MA (2007) HPLC quantification of biogenic amines in cheeses: correlation with PCR-detection of tyramine-producing microorganisms. J Dairy Res 74, 276-282

Galgano F1, Caruso M, Condelli N, Favati F (2012) Focused review: agmatine in fermented foods. Front Microbiol 3:199,1-7

Garcia-Villar N, Hernandez-Cassou S, Saurina J (2009) Determination of biogenic amines in wines by pre-column derivatization and high-performance liquid chromatography coupled to mass spectrometry. J Chromatogr A 1216, 6387-6393

Green MR, Sambrook J (2012) Molecular cloning: a laboratory manual, 4th ed. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y.

Gerner EW, Meyskens FL, Jr 2004 Polyamines and cancer: old molecules, new understanding. Nat Rev Cancer 4, 781-792

Griswold AR, Jameson-Lee M, Burne RA (2006) Regulation and physiologic significance of the agmatine deiminase system of *Streptococcus mutans* UA159. J Bacteriol 188, 834-841

Griswold AR, Nascimento MM, Burne RA (2009) Distribution, regulation and role of the agmatine deiminase system in mutans streptococci. Oral Microbiol Immunol 24, 79-82

Hopwood DA, Bibb MJ, Chater KF, Kieser T, Bruton CJ, Kieser HM, Lydiate DJ, Smith CP, Ward JM, Schrempf H (1985) Genetic Manipulation of Streptomyces: a Laboratory Manual, in: The John Innes Foundation, N., UK and Cold Spring Harbor Laboratory (Ed.)

Ignatenko NA, Besselsen DG, Roy UK, Stringer DE, Blohm-Mangone KA, Padilla-Torres JL, Guillen RJ, Gerner EW (2006) Dietary putrescine reduces the intestinal anticarcinogenic activity of sulindac in a murine model of familial adenomatous polyposis. Nutr Cancer 56, 172-181

Kelly WJ, Ward LJ, Leahy SC (2010) Chromosomal diversity in *Lactococcus lactis* and the origin of dairy starter cultures. Genome Biol Evol 2, 729-744

Kuipers OP (2001) Complete DNA sequence of *Lactococcus lactis* adds flavor to genomics. Genome Res 11, 673-674

Ladero V, Calles-Enriquez M, Fernandez M, Alvarez MA (2010) Toxicological effects of dietary biogenic amines. Current Nutrition and Food Science 6, 145-156

Ladero V, Canedo E, Perez M, Martin MC, Fernandez M and Alvarez MA (2012a) Multiplex qPCR for the detection and quantification of putrescine-producing lactic acid bacteria in dairy products. Food Control 27, 307-313

Ladero V, Coton M, Fernandez M, Buron N, Martin MC, Guichard H, Coton E, Alvarez MA (2011a) Biogenic amines content in Spanish and French natural ciders: application of qPCR for quantitative detection of biogenic amine-producers. Food Microbiol 28, 554-561

Ladero V, Fernandez M, Calles-Enriquez M, Sanchez-Llana E, Canedo E, Martin MC, Alvarez MA (2012b) Is the production of the biogenic amines tyramine and putrescine a species-level trait in enterococci? Food Microbiol 30, 132-138

Ladero V, Fernandez M, Cuesta I, Alvarez MA (2012c) Quantitative detection and identification of tyramine-producing enterococci and lactobacilli in cheese by multiplex qPCR. Food Microbiol 27, 933-939

Ladero V, Rattray FP, Mayo B, Martin MC, Fernandez M, Alvarez MA (2011b) Sequencing and transcriptional analysis of the biosynthesis gene cluster of putrescine-producing *Lactococcus lactis*. Appl Environ Microbiol 77, 6409-6418

Larsen R, Buist G, Kuipers OP, Kok J (2004) ArgR and AhrC are both required for regulation of arginine metabolism in *Lactococcus lactis*. J Bacteriol 186, 1147-1157

Linares DM, del Rio B, Ladero V, Redruello B, Martin MC, Fernandez M, Alvarez MA (2013) The putrescine biosynthesis pathway in *Lactococcus lactis* is

transcriptionally regulated by carbon catabolic repression, mediated by CcpA. Int J Food Microbiol 165, 43-50

Linares DM, Martin MC, Ladero V, Alvarez MA, Fernandez M (2011) Biogenic amines in dairy products. Crit Rev Food Sci Nutr 51, 691-703

Llacer JL, Polo LM, Tavarez S, Alarcon B, Hilario R, Rubio V (2007) The gene cluster for agmatine catabolism of *Enterococcus faecalis*: study of recombinant putrescine transcarbamylase and agmatine deiminase and a snapshot of agmatine deiminase catalyzing its reaction. J Bacteriol 189, 1254-1265

Lucas PM, Blancato VS, Claisse O, Magni C, Lolkema JS, Lonvaud-Funel A (2007) Agmatine deiminase pathway genes in *Lactobacillus brevis* are linked to the tyrosine decarboxylation operon in a putative acid resistance locus. Microbiology 153, 2221-2230

Okada T, Ueyama K, Niiya S, Kanazawa H, Futai M, Tsuchiya T (1981) Role of Inducer Exclusion in Preferential Utilization of Glucose over Melibiose in Diauxic Growth of Escherichia-Coli. J Bacteriol 146, 1030-1037

Redruello B, Ladero V, Cuesta I, Alvarez-Buylla JR, Martin MC, Fernandez M, Alvarez MA (2013) A fast, reliable, ultra high performance liquid chromatography method for the simultaneous determination of amino acids, biogenic amines and ammonium ions in cheese, using diethyl ethoxymethylenemalonate as a derivatising agent. Food Chem 139, 1029-1035

Romano A, Trip H, Lonvaud-Funel A, Lolkema JS, Lucas PM (2012) Evidence of two functionally distinct ornithine decarboxylation systems in lactic acid bacteria. Appl Environ Microbiol 78, 1953-1961

Seiler N, Atanassov CL, Raul F (1998) Polyamine metabolism as target for cancer chemoprevention (review). Int J Oncol 13, 993-1006

Simon JP, Stalon V (1982) Enzymes of agmatine degradation and the control of their synthesis in *Streptococcus faecalis*. J Bacteriol 152, 676-681

Solem C, Defoor E, Jensen PR, Martinussen J (2008) Plasmid pCS1966, a new selection/counterselection tool for lactic acid bacterium strain construction based on the *oroP* gene, encoding an orotate transporter from *Lactococcus lactis*. Appl Environ Microbiol 74, 4772-4775

Solopova A, van Gestel J, Weissing FJ, Bachmann H, Teusink B, Kok J, Kuipers OP (2014) Bet-hedging during bacterial diauxic shift. Proc Natl Acad Sci U S A 111, 7427-7432

Spano G, Russo P, Lonvaud-Funel A, Lucas P, Alexandre H, Grandvalet C, Coton E, Coton M, Barnavon L, Bach B, Rattray F, Bunte A, Magni C, Ladero V, Alvarez M, Fernandez M, Lopez P, de Palencia PF, Corbi A, Trip H, Lolkema JS (2010) Biogenic amines in fermented foods. Eur J Clin Nutr 64 Suppl 3, S95-100

Suarez C, Espariz M, Blancato VS, Magni C (2013) Expression of the agmatine deiminase pathway in *Enterococcus faecalis* is activated by the AguR regulator and repressed by CcpA and PTS(Man) systems. PLoS One 8, e76170

Wolken WA, Lucas PM, Lonvaud-Funel A, Lolkema JS (2006) The mechanism of the tyrosine transporter TyrP supports a proton motive tyrosine decarboxylation pathway in *Lactobacillus brevis*. J Bacteriol 188, 2198-2206

Table 1. Bacterial strains, primers and plasmids used in the present study.

Material	Relevant Features	Reference, source
Bacteria		
L. lactis subsp. *cremoris* CECT 8666*	AGDI cluster, putrescine producer	(Fernandez et al. 2011), CECT
L. lactis CECT 8666 Δ*agdI*	CECT 8666 knock-out for AGDI cluster	This study
Primers		
KO-214AguR-AF2	5'-CACATGACTAGTTTAGAACCTAGAAACCCAGAAAC-3'	This study
KO-214AguR-AR	5'-AACTGCAGATTTAACATCATCGGATTAGACCTAC-3'	This study
CKPstF	5'-AACTGCAGCTGCGGCAAAATTGGCAGAGCTTG-3'	This study
NoxXho	5'-CATCCGCTCGAGCCCTAATTTCTGAAGTCATTAAATATAAAC-3'	This study
Plasmids		
pCS1966	Selection/counterselection vector	(Solem et al. 2008)
pIPLA1269	pCS1966 bearing a 826 bp fragment of CECT 8666 *ycaC-aguR* genes	This study
pIPLA1292	pCS1966 bearing a 1728 bp fragment of CECT 8666 *ycaC-aguR* (826 bp) and *aguC-yrfB* (889 bp) genes	This study

*formerly *L. lactis* subsp. *cremoris* GE2-14
Restriction sites are underlined

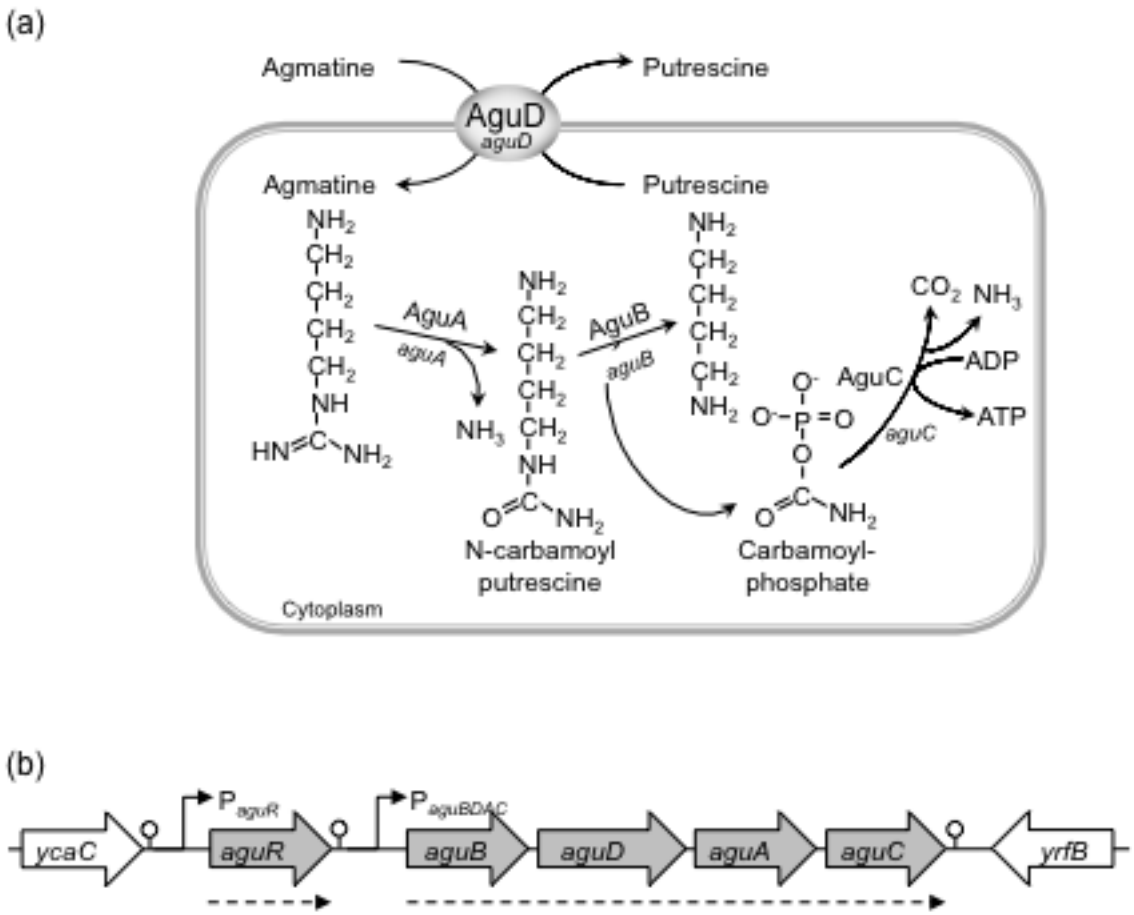
(a)
Agmatine
Putrescine
AguD
aguD
Agmatine
Putrescine
AguA
aguA
AguB
aguB
AguC
aguC
CO2 NH3
ADP
ATP
N-carbamoyl
putrescine
Carbamoyl-
phosphate
Cytoplasm
(b)
PaguR
PaguBDAC
ycaC
aguR
aguB
aguD
aguA
aguC
yrfB

Fig. 1

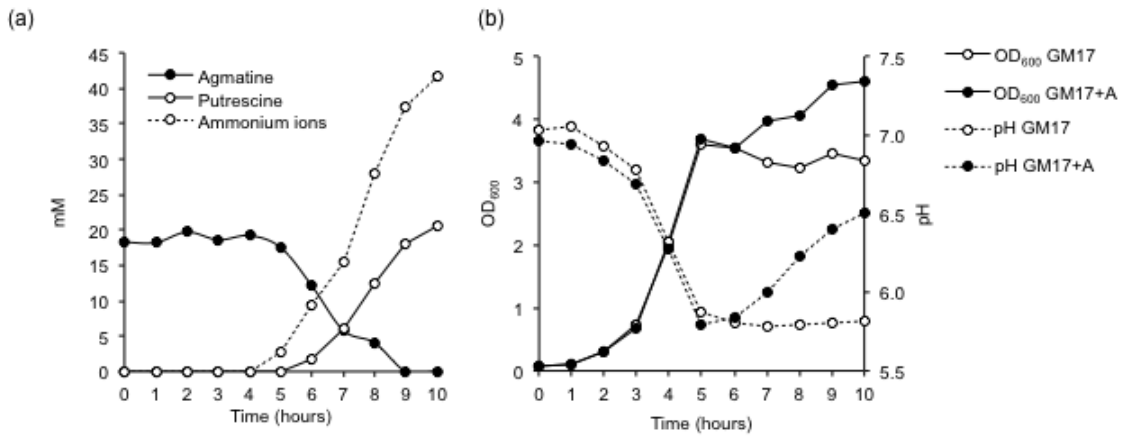
(a)
Agmatine
Putrescine
Ammonium ions
mM
Time (hours)
(b)
OD600
pH
Time (hours)
OD600 GM17
OD600 GM17+A
pH GM17
pH GM17+A

Fig. 2

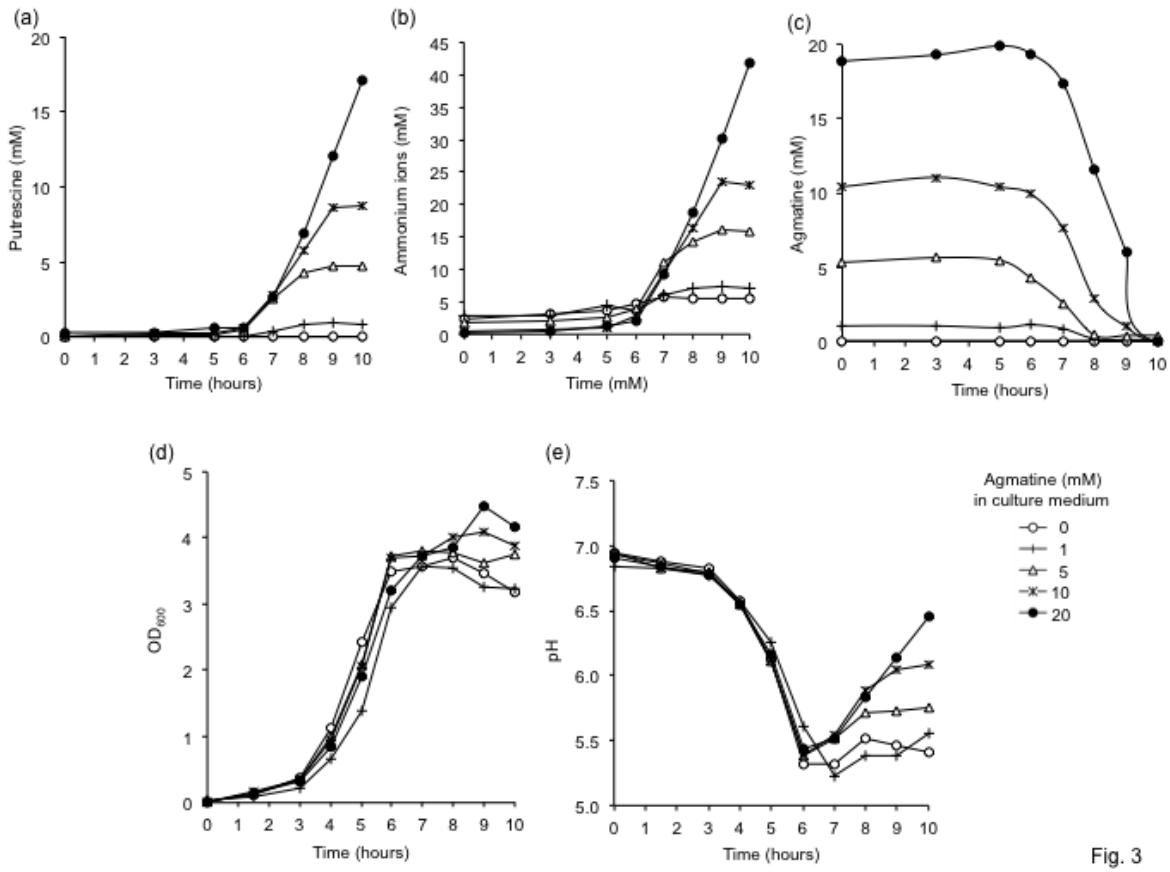
(a)
Putrescine (mM)
Time (hours)
(b)
Ammonium ions (mM)
Time (mM)
(c)
Agmatine (mM)
Time (hours)
(d)
OD600
Time (hours)
(e)
pH
Time (hours)
Agmatine (mM)
in culture medium
0
1
5
10
20

Fig. 3

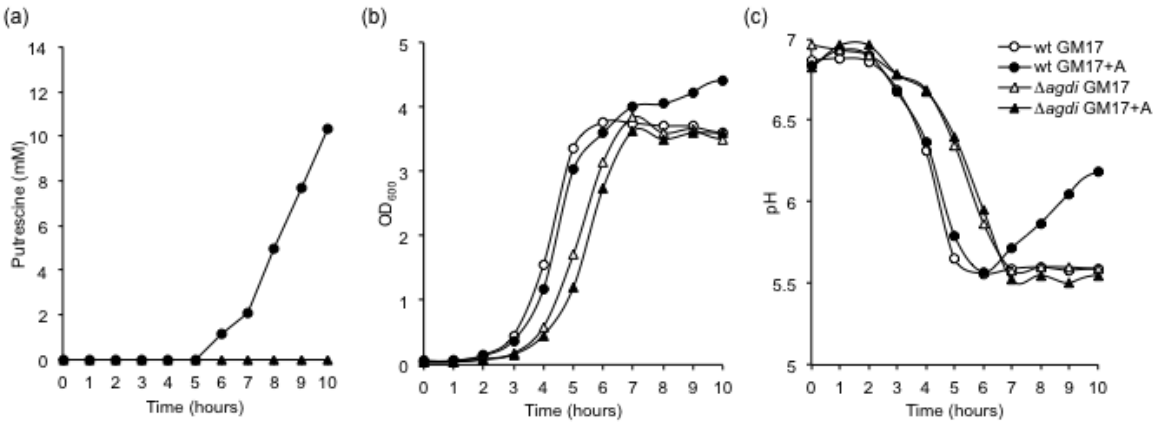
(a)
Putrescine (mM)
Time (hours)
(b)
OD600
Time (hours)
(c)
pH
Time (hours)
wt GM17
wt GM17+A
Δagdi GM17
Δagdi GM17+A

Fig. 4

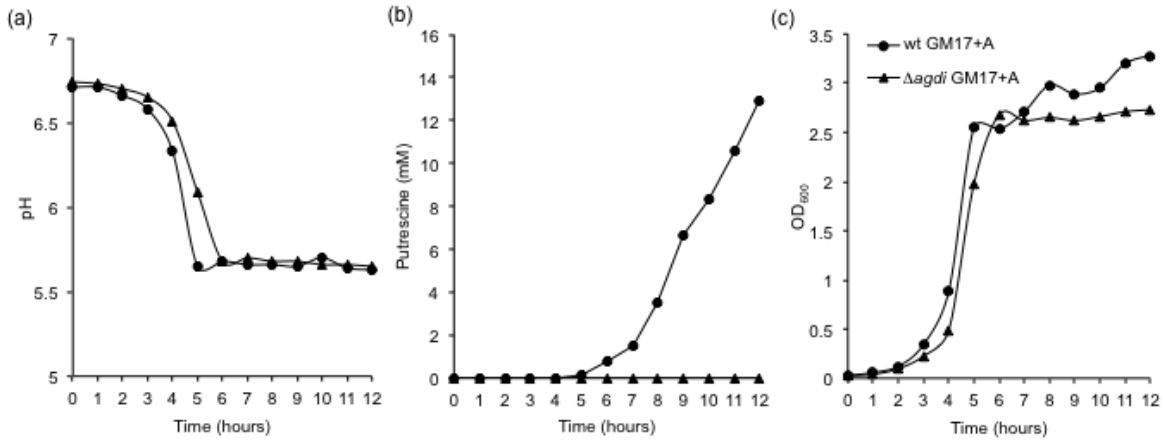
(a)
pH
Time (hours)
(b)
Putrescine (mM)
Time (hours)
(c)
wt GM17+A
Δagdi GM17+A
OD600
Time (hours)

Fig. 5